National Aeronautics and
Space Administration

RADIOISOTOPE
POWER SYSTEMS PROGRAM

A Comparison of Radioisotope and Solar Array/Battery Power
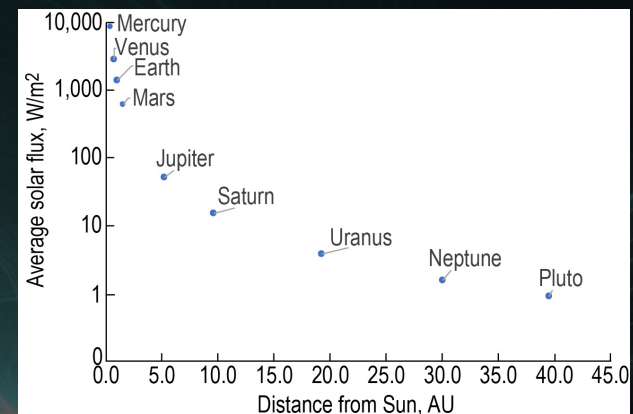Systems in the Solar System

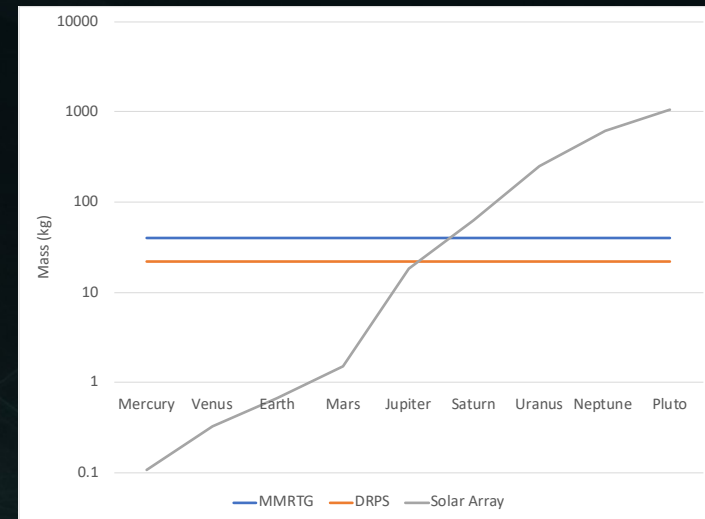IEEE Aerospace Conference Big Sky Montana

March 4-March 11, 2023

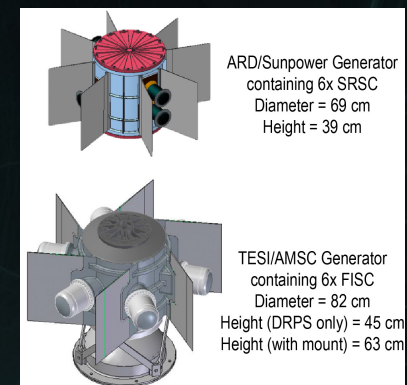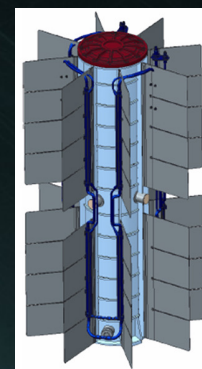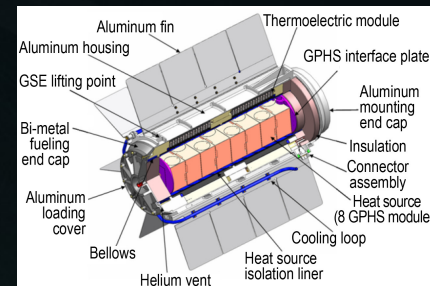Paul Schmitz

Power Computing Solutions, Inc.

Overview

- Radioisotope Power Systems (RPS) are an enabling technology for missions where solar array/battery systems are impractical
  - Low solar intensity
  - Long duration of darkness
  - Waste heat to keep spacecraft warm
- Request from Radioisotope Program Office for recreation of figure comparing RPS and solar power systems
- Figure(top) shows the mass required to provide a continuous 100 watts at various orbital locations in the solar system
  - Assumes
    - Array always faces sun
      - No periods of darkness and therefore no energy storage
    - Excluded planetary body surface operations
      - No atmosphere
- Incomplete picture of RPS utility so additional variables added
  - surface operation and energy storage

Radioisotope Power Systems

- Multi-Mission Radioisotope Thermoelectric Generator is the only available generator from DOE
  - Capable of operating in gaseous or vacuum environments with atmosphere (i.e. earth ground operations, Mars, Titan)
- NextGen RTG
  - Three Versions consideration
    - NextGen RTG Mod 0
      - Use of spare parts from GPHS RTG + possible accommodation of Step 2 GPHS modules
    - NextGen RTG Mod 1
      - GPHS RTG recreation to the extent possible with accommodation for larger GPHS (Step 2)
    - NextGen RTG Mod 2
      - New, higher performance thermoelectrics
  - Vacuum only operation
- Dynamic Radioisotope Power System (DRPS)
  - Stirling Convertors
  - High efficiency reduces isotope consumption
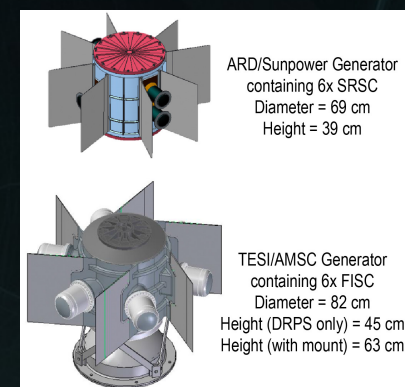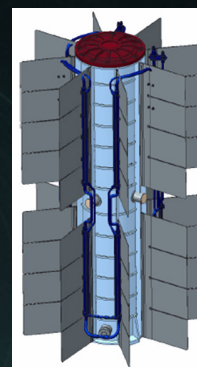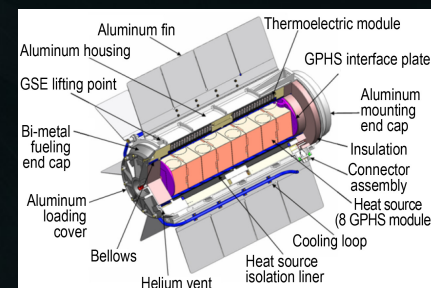 - Multi mission capability

Performance of RPS

	MMRTG	NextGen RTG Mod-1 Projected Performance	DRPS- Projected Performance
#GPHS	8	16	6
Convertor	PbTe	SiGe	Stirling
BOL power output , watts	124	245	351
EODL power output, 17 yr, watts	70	177	283
BOL efficiency	6.2%	6.1%	23.4%
Degradation Rate (DR) (%/yr) Avg over 17 years (exp(-DR*time)	3.8 %/y	1.9 %/y	1.2 %/y
BOL specific power, W/kg	2.7	4.4	3.7
Waste Heat, watts	1876	3755	1149
Relative Micrometeoroid and Orbital Debris Tolerance (MMOD)	Low	High	Medium

Aluminum fin · Thermoelectric module · Aluminum housing · GSE lifting point · GPHS interface plate · Bi-metal fueling end cap · Aluminum mounting end cap · Insulation · Connector assembly · Aluminum loading cover · Heat source (8 GPHS modules) · Bellows · Cooling loop · Helium vent · Heat source isolation liner

ARD/Sunpower Generator containing 6x SRSC
Diameter = 69 cm
Height = 39 cm

TESI/AMSC Generator containing 6x FISC
Diameter = 82 cm
Height (DRPS only) = 45 cm
Height (with mount) = 63 cm

Color Legend
Green – Available
Yellow – Small Deviation from GPHS RTG, high confidence in performance projections
Orange – New Power Convertors and Generator Design, some uncertainty in generator and convertor performance
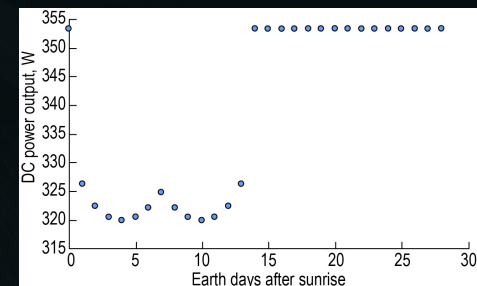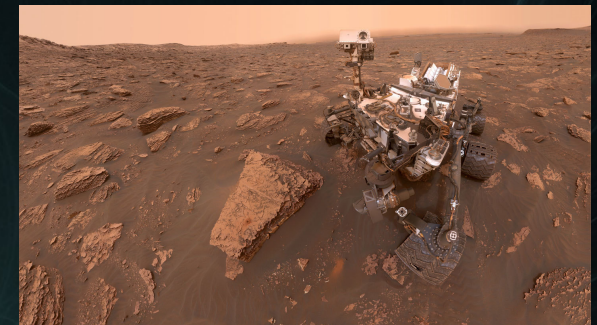
RPS in the Inner Solar System

- Two environments critical for Radioisotope Power Systems
  - Thermal
  - Chemical
- Mercury
  - Operation not possible during daylight for any of the RPS (400 C surface)
  - Operation in permanently shadowed regions or during 1408 hours of darkness should be possible and the performance should be close to that in deep space
- Venus
  - 500 C surface temperatures and 95 Bars CO_2 precludes operation on surface for any of the RPS considered
    - Some preliminary design efforts to make a RPS system capable of surface operation have been explored but these designs are not extensible to other locations
  - MMRTG or DRPS may be able to operate in the upper atmosphere but may require mission accommodation

RPS for Lunar and Mars Operation

- MMRTG
  - Lunar
    - Not designed for lunar operation and may need modification when operating near equator
      - Lower initial heat inventory
      - Protection of TE modules from MMOD
      - White paint used to reduce solar input effectiveness may be reduced due to dust accumulation
  - Mars
    - Small reductions in power output due to atmosphere thermal environment (Curiosity MMRTG power output ranged from 109 to 119 during a Martial sol)
    - Generator appears to self cleans via convection
- NextGen-Mod-0 through Mod-2
  - Lunar
    - Similar accommodations to MMRTG may be required at/near equator
  - Mars
    - Atmosphere precludes NextGen series from operation on Mars
      - Atmosphere would interact with both GPHS modules, thermoelectrics and other components
- DRPS
  - Lunar
    - Power Variations during lunar day/night cycle and location dependent
    - Current DRPS requirements should allow operation at the equator
  - Mars
    - Small power variation during Mars day/night and location dependent

Lunar Equatorial Power output of a 6 GPHS 8 Convertor DRPS with dust covering heat rejection surfaces

Other Bodies

- All the RPSs considered should be able to operate for either flyby or orbital missions from Mars out to Pluto and beyond at near deep space power output

- For landers there are 7 moons have very thin atmosphere and MMRTG and DRPS should provide power output similar to deep space operation (Ganymede, Europa, Callisto, Rhea, Dione, Enceladus, and Titania)

- NextGen RTG may have difficulties on Triton and Io's with its thicker atmosphere (component atmospheric interaction, MLI thermal conductivity)

- NextGen RTG operation on Icy world surfaces is still unknown even with very low-pressure atmospheres
  - "It would generally seem that the physical process of water sublimation and diffusion into an RTG would be unfavorable, but the potential consequence of water as a strong oxidizing agent getting into a vacuum rated RTG is significant enough that further studies would be required to understand and properly mitigate this risk" Christofer Whiting, UDRI
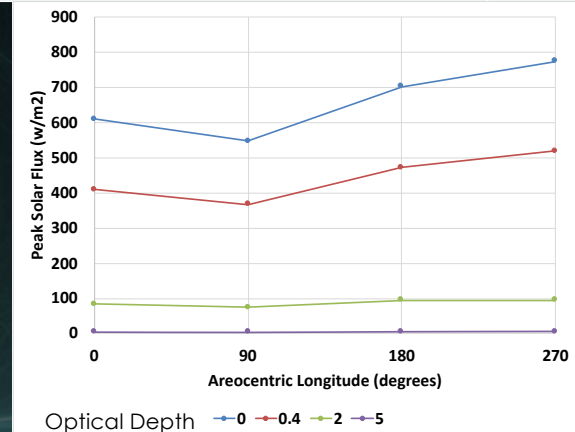
SOA Solar Array and Battery

- Solar Intensity falls as 1/Distance^2
- Solar arrays are characterized by their areal power density (w/m^2)and their Specific power (w/kg) @1 AU and then adjusted for location
  - Values are based on Northrop Grumman's Ultra Flex arrays on the Lucy Mission
- Mars operation was modeled for both Areocentric Longitude (i.e. time of year) and optical Depth
  - Optical depth values on Mars vary from about 0.4 for a clear day on Mars to 5.0 for a typical global dust storm.
    - Dust accumulation on arrays was not included
    - Largest recorded dust storm in 2018 had an optical depth >9 and caused Opportunity rover to stop working
- Titan
  - Atmospheric attenuation due to Titan's thick atmosphere is a 10-fold reduction in solar intensity
  - Surface Solar Intensity is ~1.5 w/m^2

Fold Out Flexible Array	
Conversion efficiency, %	32
Areal power density at 1 AU, W/m^2	415
Specific power at 1 AU, W/kg	184

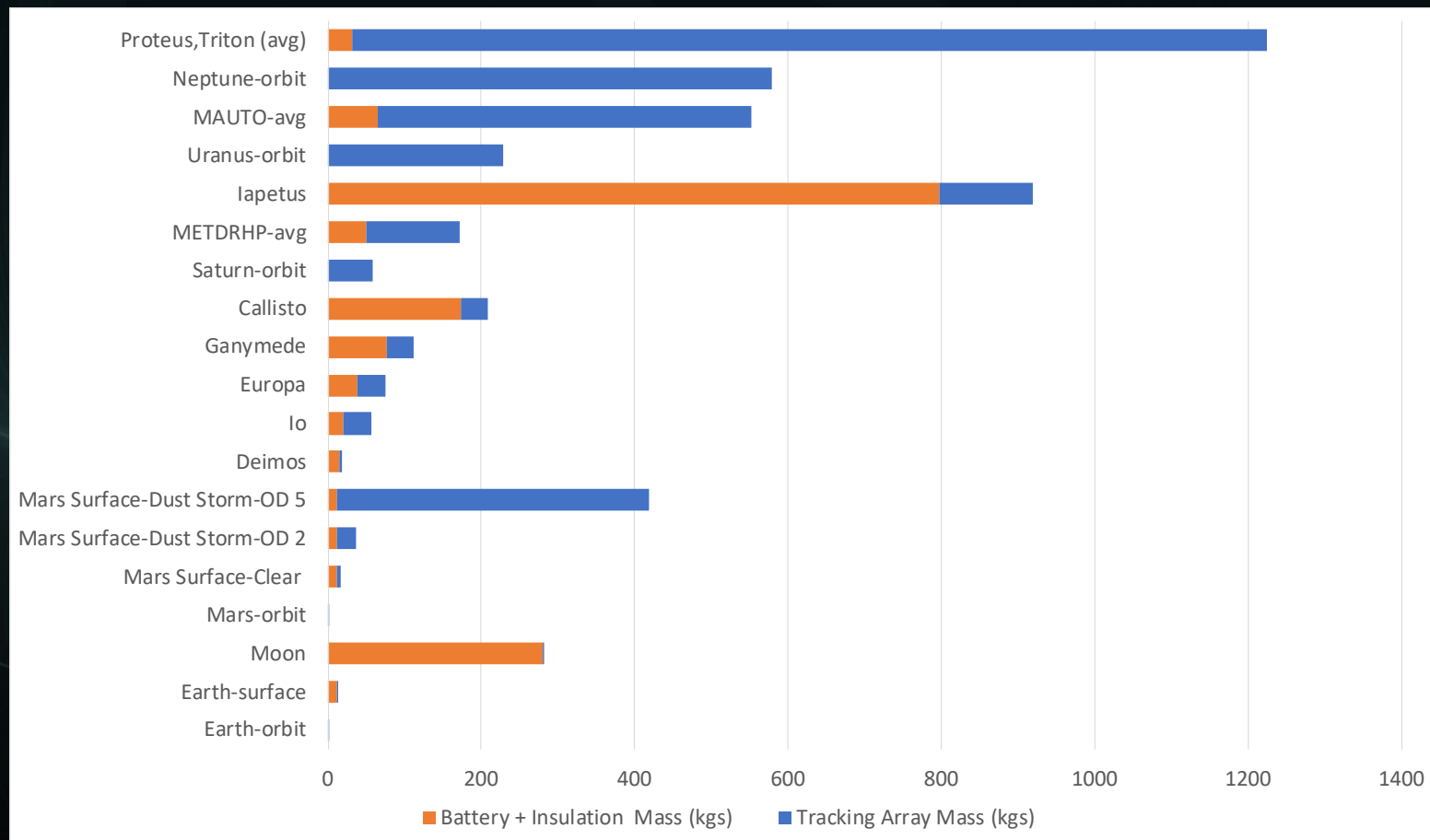| Lithium-Ion Battery SOA	
Specific energy, W-h/kg	175
Gravimetric energy density, W-h/liter	194
Depth-of-discharge, %	80
Charge/discharge efficiency, %	90

TABLE 3. Battery Performance

Solar Array/Battery systems operation throughout solar system

- Day/Night cycles were set by assuming equatorial landing
- Most moons of the solar system are tidally locked, so the bodies day equals the orbital solar period.
  - Uranus is unusual in that its axial tilt is so high that on its satellites the sun will rise and set only once per Uranus year unless the surface location is within about 8° of the equator.
  - Pluto similarly has such a high axial tilt to the plane of its orbit that any surface object more than 33° is in the polar regions.
- Following figures are for equatorial operation and show best case solar array and battery mass where day/night cycles are equal
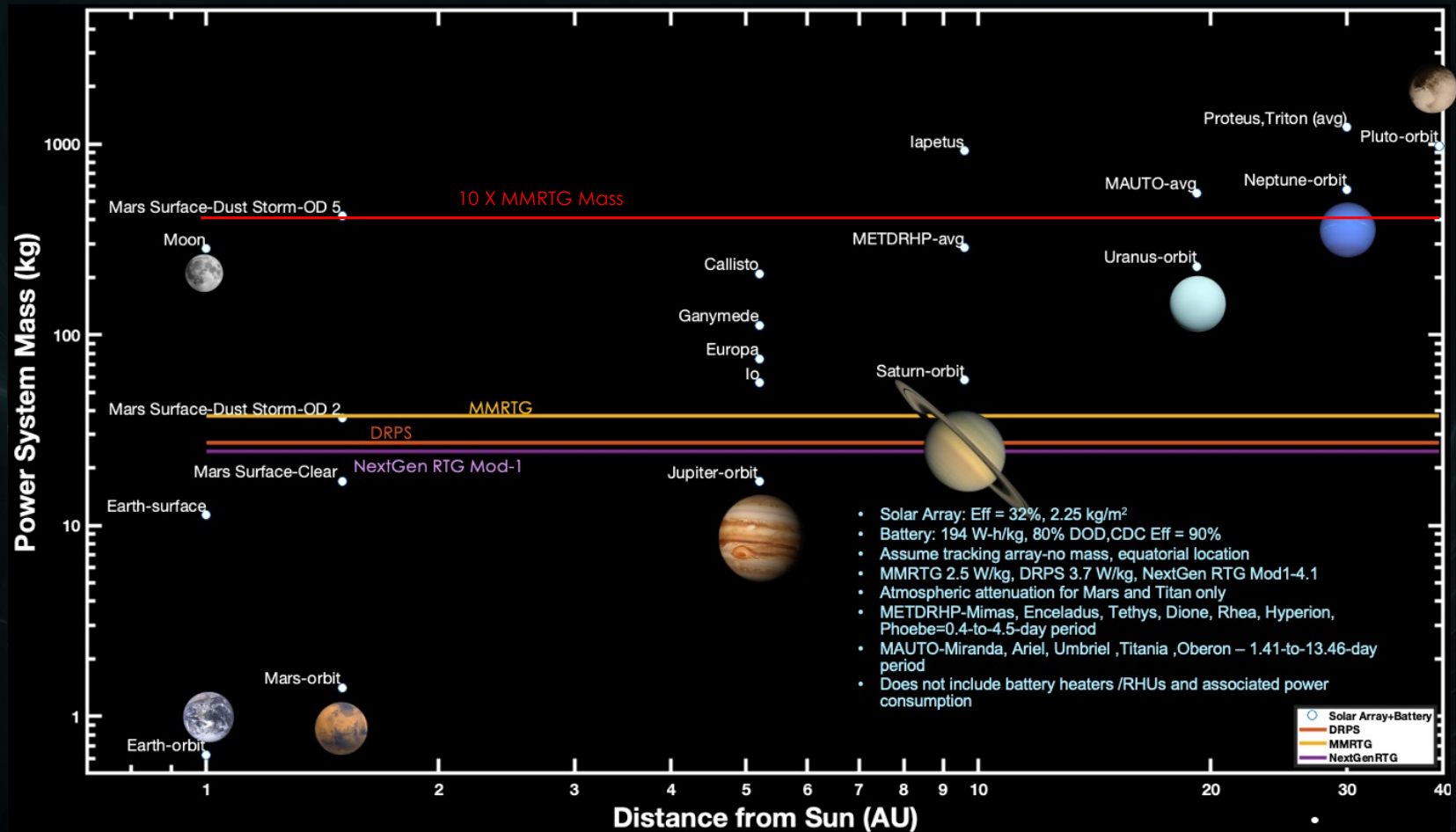 - Excluding polar regions which may have continuous illumination

Sidereal Period

Array and Battery Mass as a Function of Location

Providing 100 watts Continuous at Various Locations in the Solar System

Conclusions

- Great progress has been made in both solar array and battery storage technologies, but nuclear systems are compelling and sometimes the only alternatives of power generation for many places in the solar system

- MMRTG and DRPS Multi-Mission capability is an important feature for future exploration of icy world and other bodies

- NextGen RTG Mod-1 should provide best specific power generator for vacuum only missions

- Each RPS has their own compelling characteristics

References

- **REFERENCES**

- T.E. Hammel, R. Bennett, W. Otting, S. Fanale, "Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and Performance Prediction Model," IECEC Denver Co. August 2009.

- https://en.wikipedia.org/wiki/Dragonfly_(spacecraft)

- B. Bairstow, Y.H. Lee and K. Oxnevad, "Mission analysis for next-generation RTG study," 2018 IEEE Aerospace Conference, 2018, pp. 1-19

- J. Zakrajsek, "Radioisotope Power Systems Program," Fall Meeting of the Outer Planets Assessment Group (OPAG), August 2021

- C. Whiting, UDRI, personal communication, Jan 2022.

- S. Wilson, S. Oriti, "Convertor Development for Dynamic Radioisotope Power Systems," NETS 2020.

- DOE/INL, "NASA, INL take next step toward developing dynamic radioisotope power system," https://www.eurekalert.org/news-releases/935834, Nov 23, 2021

- Advanced Stirling Radioisotope Generator (ASRG), NASA Facts, https://rps.nasa.gov/resources/65/archival-content-advanced-stirling-radioisotope-generator-asrg/ 2013

- P.C. Schmitz, L.S. Mason, N.A. Schifer, "Modular Stirling Radioisotope Generator", IECEC 2015.

- G.M. Dugala, "Stirling Convertor Controller Development at NASA Glenn Research Center," NASA/TM–2018-219963

- C.E. Whiting, R.B. Hoffman, C.E. Barklay, P.C. Schmitz "Low Thermal Loading and Operational Voltage Limits as Methods for Enabling MMRTG as a Power Source for Lunar Missions," Big Sky Montana, March 2020.

- E. Lakdawalla, "The Design and Engineering of Curiosity," Springer Praxis Books, Cham, Switzerland 2018, ISBN: 978-3319681443.

- "Solar Power Technologies for Future Planetary Science Missions," JPL D-101316, Dec 2017

- V. Knap, L. K. Vesterguaard, D. Stroe, "A Review of Battery Technology in CubeSats and Small Satellite Solutions," Energies, August 2020

- https://www.prnewswire.com/news-releases/solaero-technologies-to-power-nasas-lucy-mission-301401745

- K.S. Novak, et al. "Mars Exploration Rover Surface Mission Flight Thermal Performance." SAE Transactions, vol. 114, pp. 118-29 (2005).

- J. Appelbaum, G.A. Landis and I. Sherman, "Sunlight on Mars: Update 1991," Solar Energy, Vol. 50 No. 1, 35-51 (1993).

- M.T. Lemmon, "Large dust aerosol sizes seen during 2018 Martian global dust storm event by the Curiosity rover," Geophys. Res. L., 2019

- A.R. Hendrix, Y.L. Yung, "Energy Options for Future Humans on Titan," J. of Astrobiology and Outreach, Vol. 5, Issue 2, June 2017

- C. M. Ernst and S. Kubota, "Mercury Lander," White paper submitted to the Planetary Science 2023-2032 Decadal Survey (August 8 2020). https://civspace.jhuapl.edu/sites/default/files/2021-05/Mercury%20Lander.pdf

- G.A. Landis, R. Dyson, S. Oleson, J. Warner, A. Colozza, and P. Schmitz, "Venus Rover Design Study," paper AIAA 2011-7268. AIAA Space 2011 Conference & Exposition, Long Beach CA, Sept. 26-29, 2011.

- https://futurism.com/the-atmospheres-on-our-moons

- Petersen, C.C., Beatty, J.K. and Chaikin, A. (eds.), The New Solar System, Sky Publishing, 1999.

- A. Petro, "Surviving and Operating Through the Lunar Night," 2020 IEEE Conference, 2020, pp. 1-6 doi:10.1109/AERO47225.2020.9172730.